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A MAJOR EARTHQUAKE IN THE STRONG CRUST: THE 1999 CHI-CHI EARTHQUAKE

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ABSTRACT

The 1999 Chi-Chi earthquake (M_W=7.6; M_L=7.3) ruptured in an area considered unusual in that, historically, large earthquakes have been unheard of and the background seismicity are low. A detailed investigation of the crustal characteristics based on seismicity, subsurface structures and GPS surveys shows that crustal strength in the low-seismicity block was most likely stronger than in the surrounding area. The earthquake took place to release large energy that had been accumulating in a strong block with low-seismicity over a long period of time. Such a strong block is associated with a pre-Miocene basement high, Peikang High, which served as a tectonic dam or barrier during the Miocene. The occurrence of the 1999 Taiwan earthquake, like many other major earthquakes such as the 1857 Fort Tejon, the 1906 San Francisco and the 1923 Kanto earthquakes, suggests that major earthquakes (M_W > 7.5) are more likely to take place in low-seismicity areas where the crust is stronger. On the other hand, moderately large earthquakes (M_W < 7) are more inclined to occur in areas of high-seismicity.

Key words: major earthquake, strong crust, low-seismicity, Peikang high

INTRODUCTION

A major earthquake occurred at 1:47 a.m. on September 21, 1999, local time, near a small town of Chi-Chi in the central part of Taiwan (referred to here as the 1999 Taiwan earthquake) (Fig. 1). The epicenter was located preliminarily at 23.87°N, 120.75°E, approximately 150 kilometers south of Taipei by a regional seismic network, the Central Weather Bureau Seismic Network (CWBSN) (Shin *et al.*, 2000). With a magnitude of M_w=7.6, as reported by the global seismic network (USGS), it was the largest inland earthquake in Taiwan ever. The death toll exceeded 2,400 and thousands of houses collapsed with more than 150,000 people homeless. It is considered the most serious disaster since World War II in Taiwan and will negatively impact the local economy for the next few years.

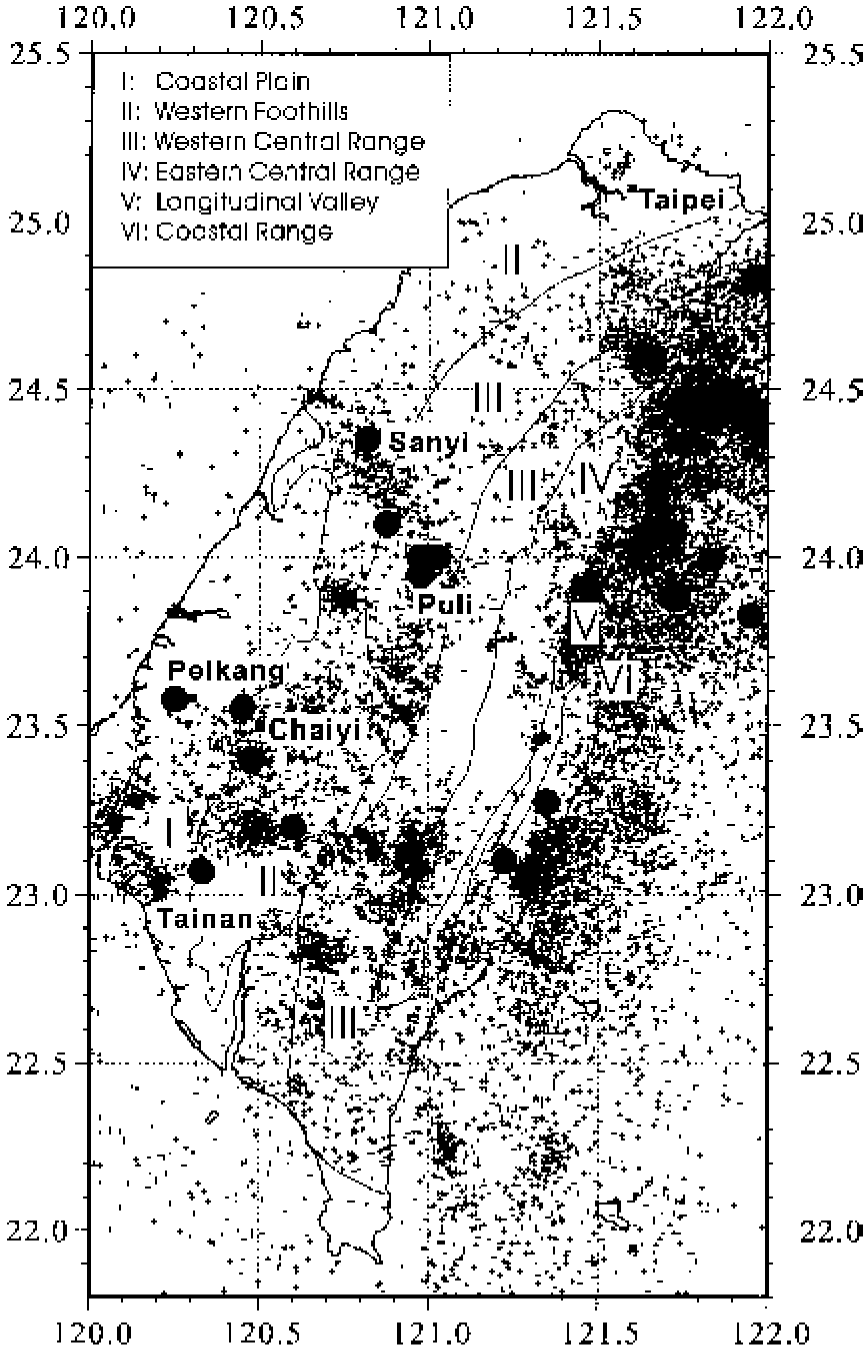

Figure 1. Background seismicity (plus signs) and large historical earthquakes (gray circles) in the Taiwan area. The epicenter of the 1999 Taiwan earthquake is indicated by the star. The geological provinces from west to east include (I) the Coastal Plain; (II) Western Foothills; (III) Western Central Range; (IV) Eastern Central Range; (V) Longitudinal Valley; and (VI) Coastal Range.

The fact that a great earthquake had been expected in the foreland belt of Taiwan due to strong plate convergence made the occurrence of the 1999 Taiwan earthquake particular because it was not located in a seismic zone, such as in the Chiayi-Tainan or Sanyi-Puli areas (Fig. 1). Instead, the earthquake occurred in a low-seismicity block where historical large earthquakes had been absent (Cheng *et al.*, 2000) and the background seismicity had been low (Fig. 1). Obviously, the occurrence of this earthquake did not conform to the popular notion that "the more micro-earthquakes there are, the greater is the risk of having a strong earthquake". On the contrary, what made the 1999 Taiwan earthquake distinct, like a few other major earthquakes, is that it occurred in a low seismicity area. Two earlier, notable examples of the same phenomenon are the 1857 Fort Tejon and the 1906 San Francisco earthquakes which occurred in areas where the number of micro-earthquakes was considerably lower than in the surrounding areas (Healy *et al.*, 1972). Similarly, the 1923 Kanto earthquake which originated in what is now a quiescent area (Shimazaki, 1971). Although the occurrence of these major earthquakes has been attributed to the concept of "seismic gap" (Rikitake, 1976), few detailed studies of the seismogenic characteristics in and around major earthquakes have been done.

To shed more light on the crustal characteristics of the major Taiwan Chi-Chi earthquake, a variety of crustal deformations recently observed in the foreland belt of Taiwan are considered in this paper. First of all, the general characteristics of crust-scale deformation have been represented by high-accuracy earthquake activities as reported by the Central Weather Bureau (CWB) and the Institute of Earth Sciences, Academia Sinica (IESAS) since 1973. Second, shallow crustal deformation has been described from the perspective of detailed subsurface structures as explored by the Chinese Petroleum Corporation (CPC) during the past few decades. Third, crustal deformation on the surface has been shown by repeated GPS surveys completed by the IESAS since 1991. In the present research all of these features are combined to investigate possible relationships between the characteristics of crust and major earthquakes.

TECTONIC AND GEOLOGICAL BACKGROUND

The island of Taiwan is located at an obliquely convergent zone between the Eurasian plate (EUP) and Philippine Sea plate (PSP). The convergent direction, as shown in Figure 1, is along N 310^{o}E with a convergent rate of about 7-8 cm/yr (Seno, 1977; Yu *et al.*, 1996). To the east of Taiwan, PSP subducts northward beneath EUP, while to the south of the island, EUP underthrusts eastward beneath PSP (Tsai *et al.*, 1977; Lin and Roecker, 1993). The geological provinces in the island of Taiwan (Ho, 1988) from west to east include (I) the Coastal Plain; (II) Western Foothills; (III) Western Central Range; (IV) Eastern Central Range; (V) Longitudinal Valley; and (VI) Coastal Range. Among them, the Longitudinal Valley is a suture zone between the two plates. East of the suture, the Coastal Range is a part of PSP. West of the suture, all geological provinces belong to EUP.

The 1999 Taiwan earthquake was centered in the Western Foothills, the geologic mapping and subsurface structures of which have been largely determined by CPC through detailed geophysical and geological analyses (Ho, 1988). The seismic profiles constrained by many wells show that the Neogene rocks were stacked up by a combination of folds and thrust faults during the Pleistocene orogeny. Deformation by thrusting and folding in the Western Foothills was active at only shallow levels, and was confined to the sedimentary cover above the pre-Miocene basement (Fig. 2). Thus, a typical decollement-style deformation has been pointed out in previous papers (Biq, 1966; Ho, 1967; Suppe, 1981, Davies *et al.*, 1983 and many others).

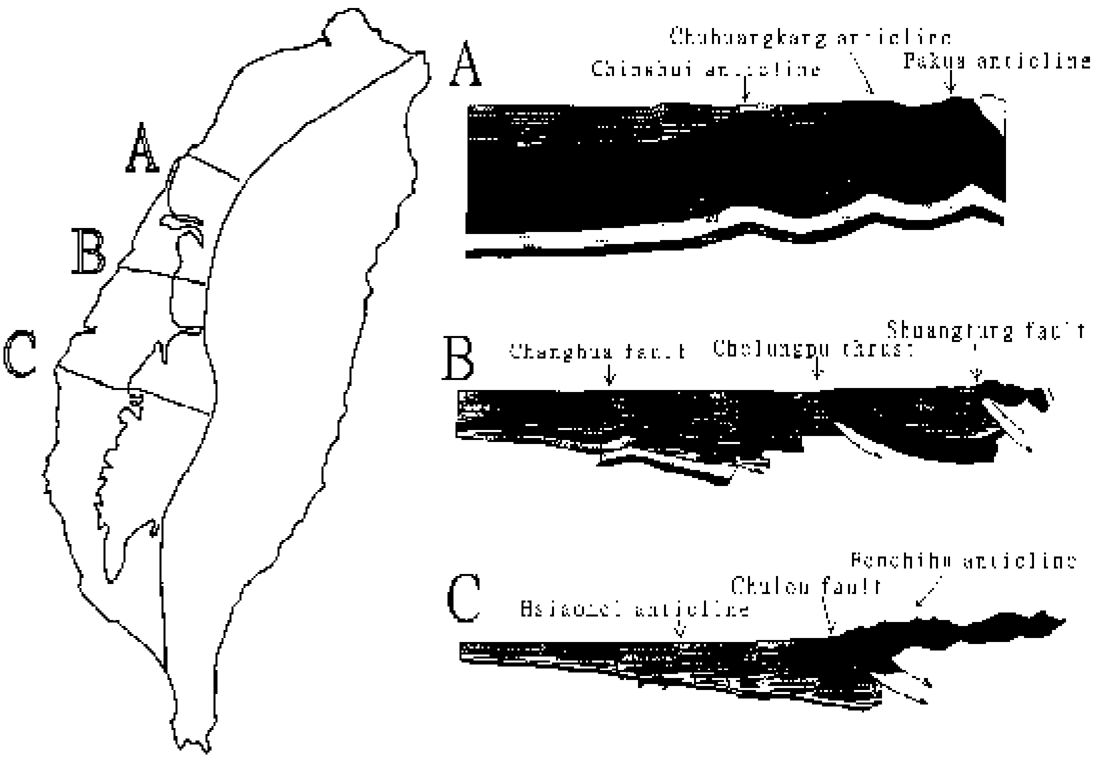

Figure 2. Subsurface structures of three geological profiles across the western Taiwan area (Modified fromHo, 1988).

In addition to the foreland belt of the thrusting and folding near the surface, it is worth noting that a pre-Miocene basement high, Peikang High, was previously identified in the central part of the western Taiwan area (Fig. 3). The highest part of this has been confirmed by well PK-2 at a depth of 1,500 meters in the vicinity of Peikang. From the point of view of tectonics, the Peikang High, shown by the eastward protruding ridge, played the role of a tectonic barrier or dam during the Miocene (Meng, 1971), and in so doing, it divided the Miocene basin of Taiwan into two parts such that the distributions of clastics and organisms are significantly different north and south of the Peikang High (Tang, 1977).

SEISMIC BACKGROUND

Strong earthquake activities in Taiwan are largely a result of plate convergence between EUP and PSP (Figures 1 and 3). Seismic activities in the northeastern and southern Taiwan regions are clearly associated with the two subduction zones (Tsai *et al.*, 1977). On the other hand, seismicity in the remaining larger part of Taiwan is more complicated and unpredictable (Lin and Roecker, 1993; Lin, 2000). In addition to strong earthquake activities in the eastern Taiwan area along the convergent boundary, clustering has been pronounced in some seismic zones such as in the Chiayi-Tainan and Sanyi-Puli areas. In contrast, earthquakes have been relatively absent in certain areas, such as, in parts of the Central Range (Lin, 2000) and Peikang High.

The 1999 Taiwan earthquake was centered at 23.75°N, 120.78°E within an area where the background seismicity (Figs. 1 and 3) and the number of aftershocks (Fig. 4) are considerably low relative to the surrounding areas. The low-seismicity block is roughly consistent with the northern part of Peikang High where there have only been a few earthquakes. Seismic activities, on the other hand, have been strong in the surrounding areas such as in the Chiayi-Tainan and Sanyi-Puli seismic zones. Such a distinction is also observable from the distribution of moderately large historical earthquakes plotted in Figure 1.

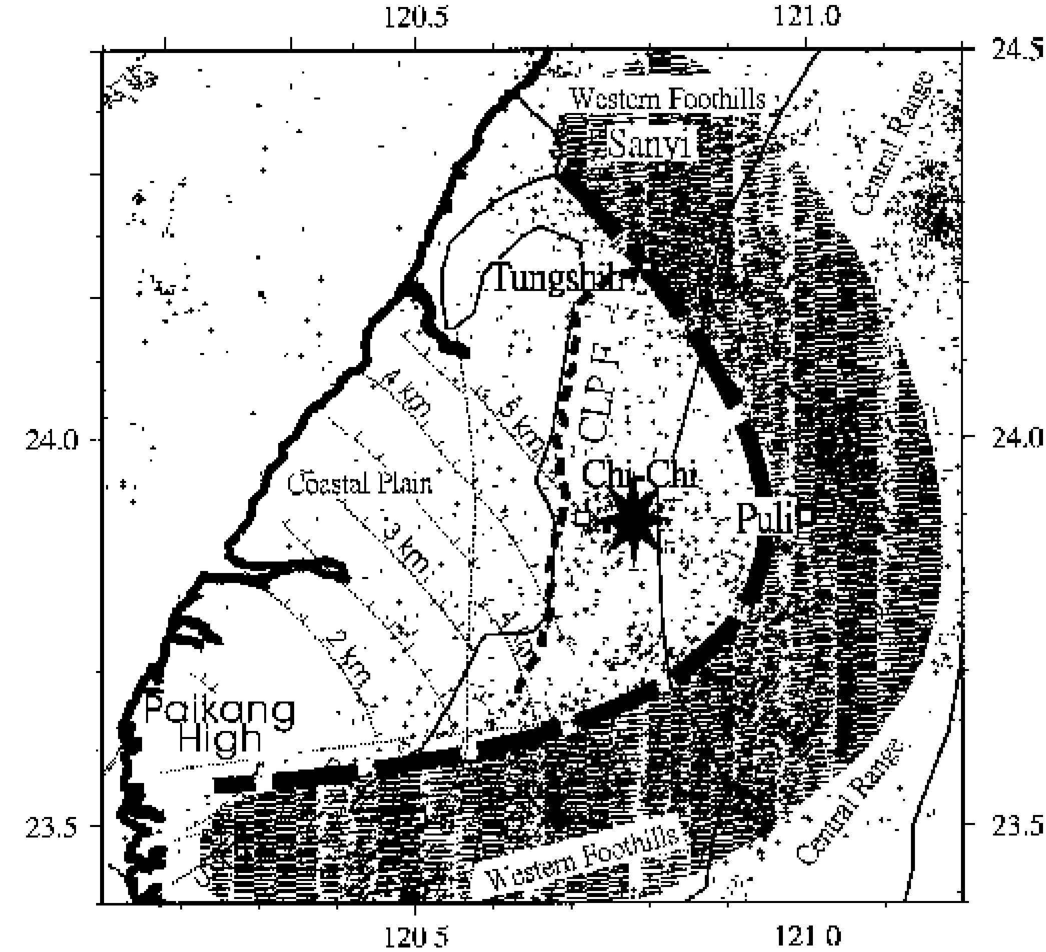

Figure 3. Epicenter of the 1999 Taiwan earthquake (large star) and background seismicity (plus signs) with magnitudes greater than 2.0 recorded from 1973 to 1998 in Taiwan. The thick dashed line delineates the eastern boundary of the low-seismicity block in the western part of Taiwan. West to the low-seismicity block, strong seismic activity is shown by the shaded area. The main geological boundaries (solid lines), the Chelungpu fault (CLPF: thick dashed line) and the basement high (ticked lines) are also plotted.

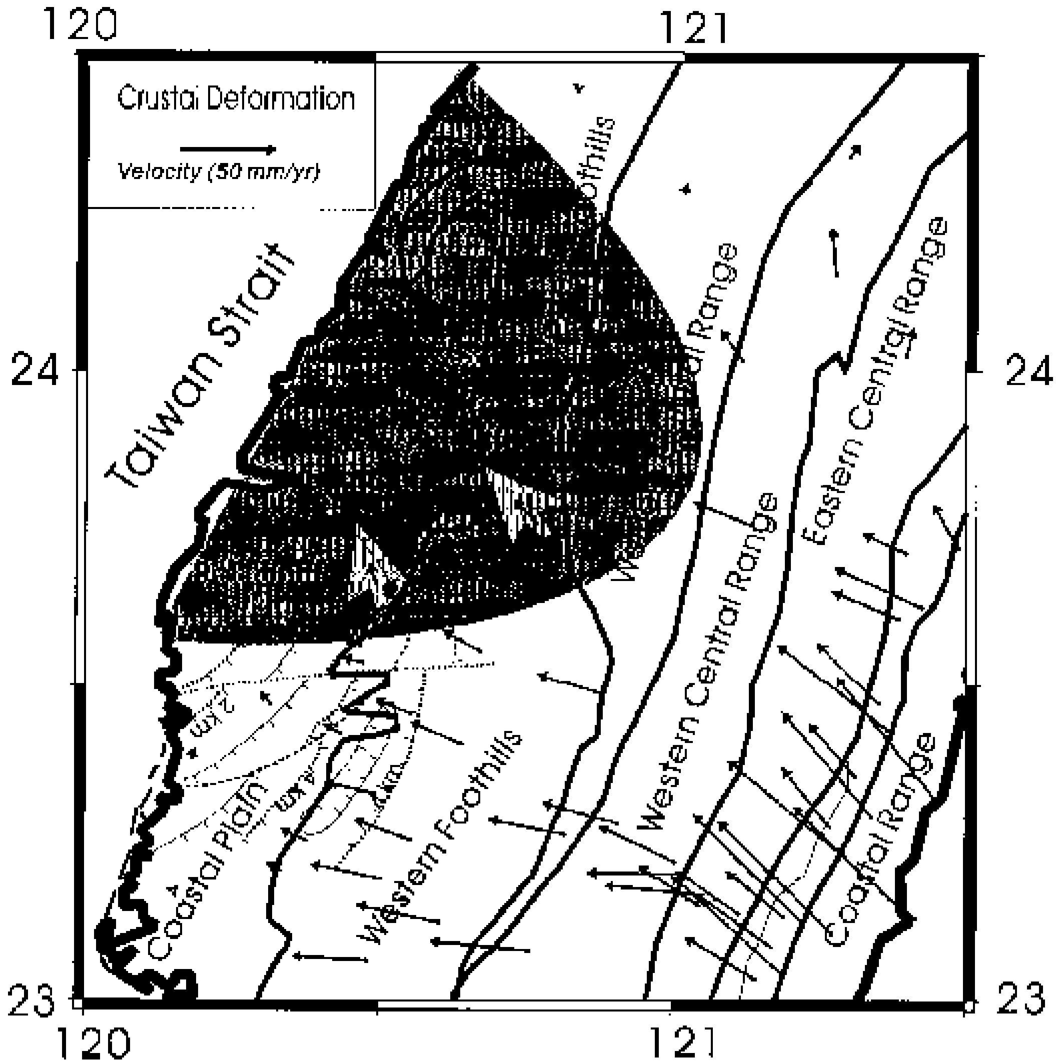

Figure 4. Crustal deformation measured from the GPS network in central Taiwan. Small vectors show the velocity of the strain rate at each station. The pre-Miocene basement is shown by iso-depth contours.

GPS SURVEYS

The velocity fields of crustal deformation in Taiwan have been obtained from GPS surveys since 1991 (Yu *et al.*, 1996). In general, small crustal deformation (less than a few millimeters per year) was measured in the Coastal Plain (or Peikang High), while significant deformation with velocity of tens of millimeters was found in the Western Foothills and Central Range. In addition to the general pattern of a gradual decrease toward the west, the velocity fields in central Taiwan show some interesting spatial variations (Fig. 4). First, it is noteworthy that the velocity field of the crustal deformation in the northern part of the Western Foothills is significantly less than that in the southern part. Second, the velocity vectors systematically change from east to west. In the Coastal and Eastern Central Ranges, crustal deformation consistently points to the NW (305-320^o), which agrees with the convergence direction between the Eurasian and Philippine Sea plates (Seno, 1977). However, the velocity vectors slightly change direction when they come close to the Peikang High. The vectors rotate clockwise from NW to NNW in the northern part of the Western Central Range, whereas they rotate anti-clockwise and almost become westwardly in the southern part of the Western Central Range and Western Foothills. Velocity vectors with small strain roughly point inward when they pass through the eastern convex boundary of the low-seismicity block in the northern part of the Peikang High.

DISCUSSION

Since variations in crustal deformation under the same stress pattern reflect the physical characteristics of rocks, the general characteristics of crustal strength in the central part of western Taiwan might very well be represented by crustal deformation evaluated from GPS surveys, subsurface structures and seismicity. In other words, the stronger the crust is, the smaller crustal deformation there is. The stress pattern in the western Taiwan area largely results from the convergence between PSP and EUP (Lin *et al.*, 1985; Yeh *et al.*, 1991). It follows then that crustal deformation in the central part of western Taiwan might be considered to be under the same stress pattern, and as such, the variations in crustal deformation probably mirror the detailed characteristics of crustal strength.

Crustal deformation in central Taiwan indicates that crustal strength in the northern part of the Peikang High is probably greater than that in the surrounding areas. First of all, the results of the GPS surveys on the surface suggest that there is a strong block in the Peikang High (Fig. 5), where strain fields of crustal deformation, particularly, in its northern part, are slightly less than those in the surrounding areas. In addition, the phenomenon of systematically changing velocity vectors when they approach the Peikang High implies that the Peikang High serves as a strong backstop in the progression of the foreland belt in western Taiwan.

Second, background seismicity, which often represents part of the crustal deformation in the brittle upper crust, shows that the northern part of the Peikang High is a low-seismicity block. This is different from the surrounding areas where a lot of earthquakes have been reported, such as in the Chiayi-Tainan and Sanyi-Puli seismic zones. Such a distinction is also apparent in the aftershock distribution of the 1999 Taiwan earthquake (Figure 5). Off-hand, a few explanations for the characteristics of low-seismicity within the crust might be made. It might first be said that earthquakes do not occur if there is no stress applied to the crust. Alternatively, the presence of a low-seismicity zone within the crust could indicate that it is either stronger or more ductile than the surrounding areas. Obviously, both of these possibilities, there being no stress applied and it not being ductile, must be ruled out due to the occurrence of the mainshock in the low-seismicity block. The strong contrast of both background and aftershock seismicity again implies that crust strength in the Peikang High is probably stronger than in the surrounding areas.

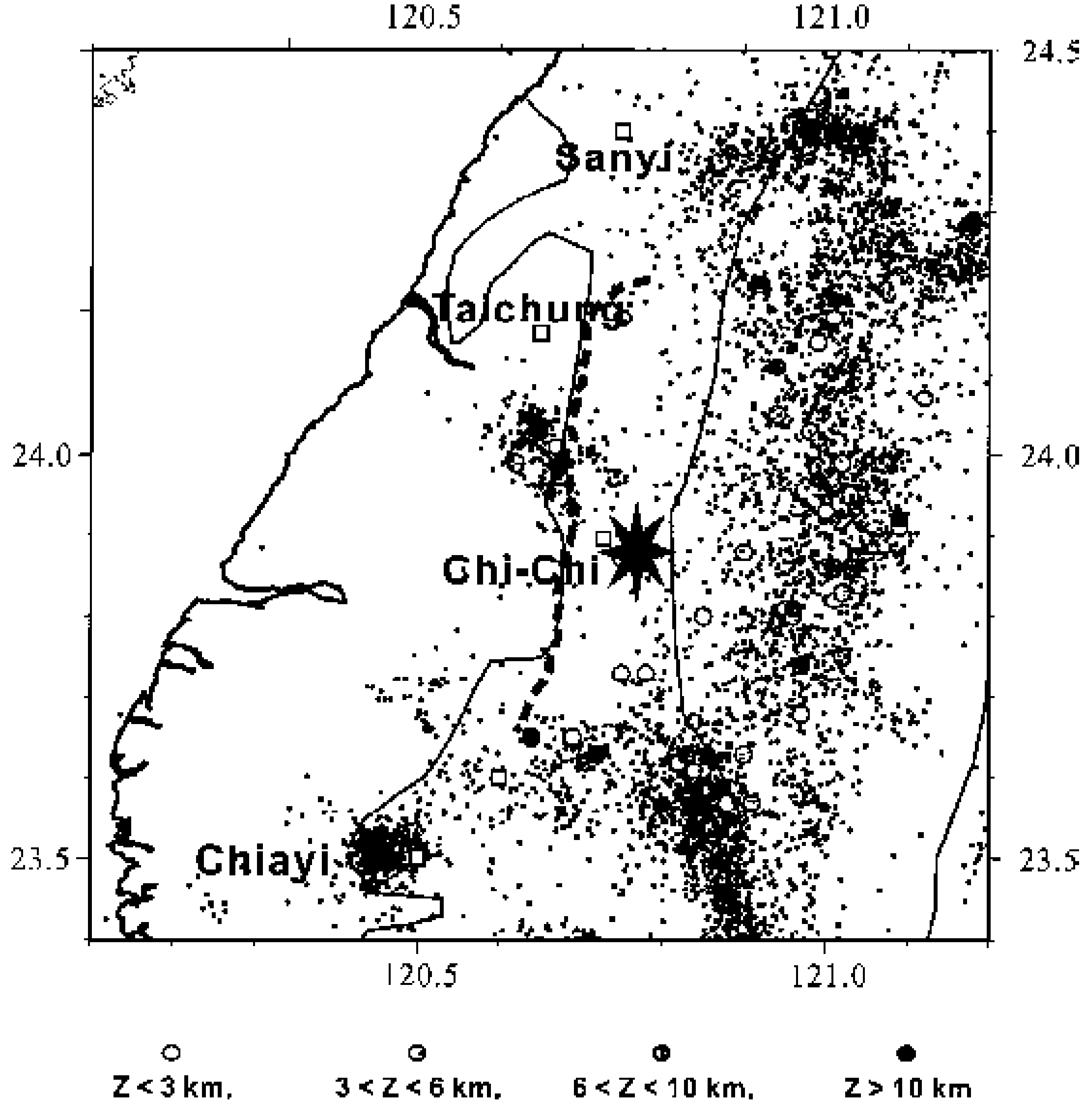

Figure 5. Aftershock pattern of the 1999 Taiwan earthquake during the first three months (provided by the CWB). The location of the mainshock (M_w=7.6), large aftershocks (M_L>3.5) and smaller aftershocks (M_L<3.5) are marked by the star, gray circles and dots, respectively. Significant surface rupture, largely along the Chelungpu fault, is indicated by the dashed line.

Third, subsurface structures in western Taiwan show that the characteristics of rock deformation in the Peikang High are significantly different from those in the surrounding areas (Ho, 1988). Subsurface structures cutting through the Peikang High (Profile B in Figure 2) are largely dominated by thrust faulting with a significant slip of about a few kilometers. Such a large-slip (Profile B) indicates that the strata are more brittle than ductile. On the other hand, subsurface structures to the north and south (Profiles A and C in Figure 2) are generally represented by significant folding and small faulting. Significant folding shown by several anticlines such as the Chinshui, Chuhuangkeng, and Pakuali anticlines in Profile A as well as the Hsiaomei and Fenchihu anticlines in Profile C implies that strata are more ductile than brittle.

In addition to low-seismicity, a small strain rate and thrusting-dominant subsurface structures, the physical modeling of sandbox experiments shows that the Peikang High acts as a strong back-stop in the progress of foreland fold-and-thrust structures (Lu *et al.*, 1998). All of these phenomena indicate the crustal strength in the northern part of the Peikang High is probably stronger than that in the surrounding areas.

One feasible explanation for the phenomenon of stronger crust in the Peikang High is the variation in basement relief in the western part of central Taiwan, although there may exist many other more complicated factors such as an inhomogeneous distribution of rock contents, pore pressure and heat flow (Brace and Byerlee, 1970; Byerlee, 1978). Since the pre-Miocene basement had experienced significant upheaval in the central part of western Taiwan, it played the part of a tectonic barrier or dam during the Miocene (Meng, 1971). In other words, at the same depth, the rock strength of the basement is obviously greater than that of the surrounding strata deposited by thick Miocene sediments. As a result, in the upper crust, the rock strength of the Peikang High with thick basement rock and thin sediments is obviously greater than that in the surrounding areas at the same depth (Fig. 6). However, the low-seismicity block does not coincide with the Peikang High, except in the northern part. This phenomenon might be explained by the detailed subsurface structures. The seismic profiles constrained by many wells show that the basement high can be divided into two parts by an east-west-trending normal fault, fault "B" (Stach, 1957). Fault B serves as a hinge-line fault, where a rapid transition from a shelf to a deep basin is expected to occur south of the fault. Vertical offset along Fault B is about 500-1,000 meters. In addition, north of fault "B" the strata dip gently to the northeast, but south of the fault they dip to the south-southeast (Fig. 3). The abrupt turn implies that the block south of fault "B" has been subjected to shear stress with dextral movement and clockwise rotation along fault "B" (Tang, 1977). Such detailed subsurface structures indicate that at the same depth the rock strength in the southern part of the Peikang High was probably weaker than that in the northern part.

In summary, the scenario of the 1999 Taiwan earthquake was similar to that of many other major earthquakes in the world, such as the 1857 Fort Tejon and the 1906 San Francisco earthquakes. They indicate that major earthquakes (M_w > 7.5) have a tendency to take place in low-seismicity areas where the crust is stronger. For a strong crust, rock strength is greater than that in the surrounding areas, and the seismicity that represents part of the crustal deformation is absent. Although there is no significant seismic activity in the strong crust, a lot of stress energy accumulates before failing. Eventually, a major earthquake is induced to release large energy that has accumulated in the strong crust over a long period of time. Since a major earthquake may take a longer time to accumulate the larger stress energy required to overcome the rock strength in the stronger crust, the released energy is greater than with moderately large earthquakes in a seismic zone. Unlike a major earthquake in an area of low-seismicity, moderate historical large earthquakes of magnitudes between 6 and 7. 3 often take place in fracture zones or weaker crusts where micro-earthquakes are frequent. Such a distinction indicates that it is important that the traditional hazard analysis of microzonation, which is usually determined by large historical earthquakes and micro-earthquakes, be reconsidered because a potential major earthquake, of magnitude greater than 7.5, might not just be located in a seismic zone.

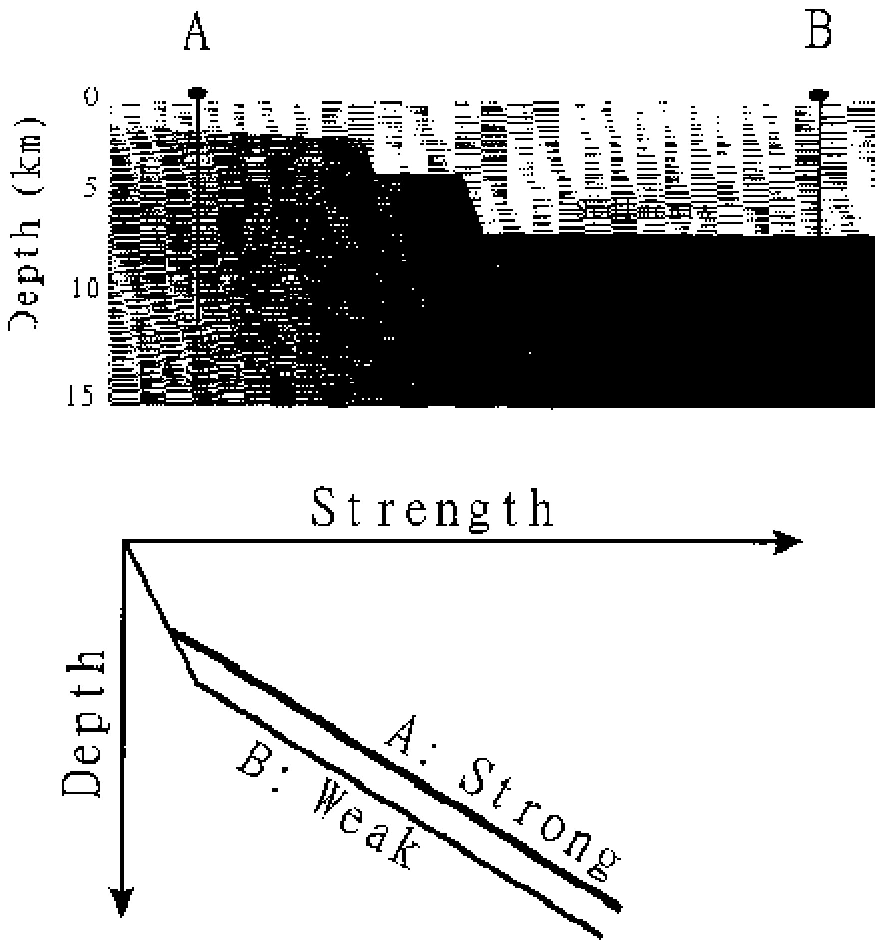

Figure 6. Schematic plot of the variations in crustal strength with subsurface structures. In the upper part, the sediments on the left-hand side beneath Point A (higher basement) are thinner than that on the right-hand side beneath Point B. In the lower part, at the same depth the strength of the upper crust beneath Point A is always stronger than that beneath Point B.

CONCLUSIONS

The physical properties of the upper crust inferred from crustal deformation in the western part of central Taiwan show that the 1999 Taiwan earthquake occurred in a strong crust. The strong block correlates with the northern part of the Peikang High, which was an important tectonic dam in Miocene. The crustal deformation in the strong crust is represented by small strain fields on the surface, large-slip faultings near the surface and low-seismicity in the upper crust. On the other hand, a systematic rotation of strain fields, high-seismicity and significant foldings are found in the surrounding areas of the strong crust. Occurrence of a major earthquake in a low-seismicity block would demand that the traditional hazard analysis of microzonation usually based on the pattern of large historical earthquakes and micro-earthquakes should be reconsidered critically.

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